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Photospheric phosphorus in the FUSE spectra of GD71 and two similar DA white dwarfs

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ABSTRACT
We report the detection, from FUSE data, of phosphorus in the atmospheres of GD71 and two similar DA white dwarfs. This is the first detection of a trace metal in the photosphere of the spectrophotometric standard star GD71. Collectively, these objects represent the coolest DA white dwarfs in which photospheric phosphorus has been observed. We use a grid of homogeneous non-LTE synthetic spectra to measure abundances of [P/H]=$-8.57^{+0.09}_{-0.13}$, -8.70$^{+0.23}_{-0.37}$ and -8.36$^{+0.14}_{-0.19}$ in GD71, RE J1918+595 and RE J0605-482 respectively. At the observed level we find phosphorus has no significant impact on the overall energy distribution of GD71. We explore possible mechanisms responsible for the presence of this element in these stars, concluding that the most likely is an interplay between radiative levitation and gravitational settling but possibly modified by weak mass loss.

Key words: stars: abundances, white dwarfs; stars: individual: GD71

1 INTRODUCTION

The compositions of the atmospheres of white dwarfs are observed to be dominated by the lightest elements, H (DAs) or He (DO/DBs), as predicted several decades ago by theory (Schatzman 1958). Unimpeded, the high surface gravities of these objects cause heavier elements to settle out on timescales of mere days (e.g. Dupuis et al. 1993). Nevertheless, ultraviolet observations have revealed trace quantities of metals in the photospheres of a large number of hot white dwarfs ($T_{\rm eff} \gtrsim 40000$K), e.g. C, Fe and Ni in G191-B2B (Bruhweiler & Kondo 1983, Vennes et al. 1992, Holberg et al. 1994) and a handful of cooler degenerates e.g. Si in Wolf 1346 ($T_{\rm eff} \approx 20000$K; Holberg et al. 1996). Furthermore, high resolution optical spectroscopic observations have shown that $\sim$20% of DAs cooler than 10000K are DAZ stars, that is they contain observable quantities of Ca, Mg, and Fe (Zuckerman et al. 2003). Clearly, there are processes operating in the photospheres of these objects which can compete against gravitational settling.

Several theoretical studies have shown that the transfer of net upward momentum from the intense radiation field to heavy elements via their bound-bound transitions can prevent small but detectable quantities of metals from sinking out of the photospheres of white dwarfs with $T_{\rm eff}\gtrsim$20000K(e.g. Vauclair, Vauclair & Greenstein 1979). A number of these investigations have made relatively precise predictions regarding the abundances of heavy elements as a function of surface gravity and effective temperature (e.g Chayer et al. 1995a, Schuh 2005). Indeed, these calculations are able to qualitatively reproduce some of the more general trends, affirming radiative levitation as an influential mechanism in preventing gravitational settling in the atmospheres of these hotter stars. For example, they successfully replicate the observed sharp decline in the abundance of Fe at $T_{\rm eff}\approx$50000K and the observed decrease with $T_{\rm eff}$ in the overall metal content of white dwarf photospheres. Further, in accord with these calculations the abundances of elements such as C and N appear to be largely independent of effective temperature at $T_{\rm eff}\gtrsim$50000K (see Barstow et al. 2003).

However, at a more quantitative level, there are significant discrepancies between observed heavy element abundances and the predictions of equilibrium radiative levitation theory. On theoretical grounds, stars with comparable effective temperatures and surface gravities are expected to have similar photospheric abundances, but in reality can show radically different compositions. For example, while the observed energy distribution of GD153 is consistent with that of a pure-H atmosphere, GD394 and RE1614-085 contain significant quantities of silicon ([Si/H]=-5.1$\pm$0.1) and nitrogen ([N/H]=-3.6$\pm$0.1) respectively, despite all three objects having $T_{\rm eff}\approx$38000K and log g$\approx$7.8 (Holberg et al. 1997). It has often been argued that these anomalies indicate other processes (e.g. accretion or massloss), act in conjunction with radiative levitation, at least in some stars, to dictate photospheric composition.

Our survey of the abundances of C,N,O,Si,Fe and Ni in the photospheres of 25 hot DA white dwarfs is the most comprehensive undertaken to date and unearthed a number of interesting results (see Barstow et al. 2003). However, it was based largely on HST

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Table 1. The log of the FUSE observation of GD71.

Observation ID	Aperture/mode	Start date	Exp. time (secs.)
P2041701000	LWRS/TTAG	00-Nov-04	13928

STIS data, a sample that cannot now be enlarged due to instrument failure. To gain a more complete understanding of the relative influence of each of these physical processes it is important to continue enlarging the sample of stars for which robust measurements and limits on the abundances of photospheric metals are available. Further, it is particularly important to increase the number of such stars in effective temperature ranges where few objects have previously been studied (e.g. 20000K$\lesssim$$T_{\rm eff}$$\lesssim$40000K). Over the last few years the Far Ultraviolet Spectroscopic Explorer (FUSE) has observed a large number of white dwarfs. This has led to the provision of a collection of homogeneous spectroscopic data covering $\lambda\approx$900-1200Å with generally moderate to good signal-to-noise, for $\gtrsim$100 DAs. Much of this data is now in the public domain and available for download from the Multimission Archive at Space Telescope (MAST). These FUSE observations offer the benefit over IUE and HST data of access to resonance lines of P and S. Thus photospheric abundance surveys can now be expanded to include these two additional elements.

GD71 (WD0459+158), first catalogued by Giclas et al. (1965), is a bright nearby hot DA white dwarf lying virtually in the middle of the aforementioned temperature range ($T_{\rm eff}\approx$32000K). It has been studied extensively at optical, UV, EUV and near-IR wavelengths and is widely used as a photometric and spectrophotometric calibration star (e.g. Landolt 1992, Bohlin et al. 2001). Within their respective statistical uncertainties, the International Ultraviolet Explorer (IUE) and Extreme Ultraviolet Explorer (EUVE) spectra of GD71 are entirely consistent with a pure-H atmosphere and to date no heavy elements have been detected in its photosphere (Barstow et al. 1997, Holberg et al. 1998). Indeed, for spectrophotometric calibration purposes it has been assumed to have a pure-H composition (e.g. Bohlin 1996). However, we have chosen to examine this assumption more closely, since 1) radiative levitation theory predicts the presence of small but nevertheless detectable quantities of photospheric metals down to $T_{\rm eff}\approx$20000K (e.g. Si, Al and P), 2) to date only a handful of objects have been studied in detail in the range 20000K$\lesssim$$T_{\rm eff}$$\lesssim$40000K and 3) there exists a FUSE spectrum with good S/N ($\sim$30) for this white dwarf.

In the current work we present an analysis of the FUSE spectrum of GD71. We identify a number of spectral features attributable to the interstellar medium. In addition, we detect high ionization P features which we argue arise in the stellar photosphere. We use a grid of non-LTE model atmospheres to determine [P/H]. Finally, we discuss our findings in the context of radiative levitation theory and the processes of accretion and mass-loss.

2 OBSERVATIONS

2.1 A FUSE observation of GD71

An observation of GD71 was obtained with FUSE operating in TTAG mode and in the LWRS configuration on 2000/11/04. We have acquired the relevant raw data products from the Multimission Archive at the Space Telescope Science Institute (MAST). A summary of this observation is presented in Table 1.

Several detailed descriptions of the FUSE instrumentation already exist in the literature (e.g. Green, Wilkinson & Friedman 1994), so we only give a brief description of the features most relevant to the current analysis. The spectrometer consists of four separate optical channels. To maximize the throughput, it is important that all four are properly illuminated by the target. However, it has proved difficult to maintain optimal alignment for the duration of an observation due to in-orbit movement in the mirrors and gratings. Consequently, most observations have been obtained through the large square aperture (30"x30") of the LWRS configuration which limits the spectral resolution to between R=10000-20000.

We have processed the raw data with a recent version of CALFUSE (v3.0). The pipeline procedure nominally flux and wavelength calibrates the data, correcting for geometric distortions and flagging as low quality data obtained on deadspot areas of the detectors. However, this version of the software does not correct for the impact on the count rates of the "worm", a strip of flux attenuated by up to 50%, running in the dispersion direction of the spectra. An inspection of the count rate plots for each channel produced by the pipeline suggests that GD71 remained comfortably within the LWRS apertures throughout the duration of this observation. Furthermore, an examination of the individual extracted 1D spectra indicates that the "worm" only affected LiF 1b data significantly.

Prior to coadding the individual datasets to obtain a single FUV spectrum of GD71 with optimal S/N, it was necessary to account for drifts in the wavelength scale between the subintegrations of the observation. The exposures for each segment were cross correlated by running the the IDL routine CROSS-CORRELATE on the regions which included the most distinct absorption features (e.g. the NI triplet at 1134Å for LiF 1b and Lif 2a). Small wavelength corrections were calculated and applied to the data. The alignments of the exposures for each segment were examined by eye, and, where improvement was necessary or possible (e.g. where geocoronal emission had impacted on the results of CROSS-CORRELATE algorithm), further small shifts applied manually to their wavelength scales. A co-added dataset for each segment was then produced where each subintegration was weighted according to exposure time. Any data found to be significantly affected by the worm were discarded. As they generally have the lowest S/N and the poorest wavelength solution, data from the edges of each spectrum were also rejected. Sections of these datasets which include strong absorption lines were cross correlated and any linear wavelength shifts with respect to the LiF 1a segment calculated and applied to each. However, the FUSE spectrum of GD71 contains no strong absorption features in the ranges 995-1010Å and 1090-1110Å. Therefore the measured wavelengths of sharp line features arising from species HI, CII, OI, and NI, which were assumed to have a common interstellar origin, were used to apply a fine adjustment to the wavelength scales of the SiC 1b, SiC 2a, LiF 1b and LiF 2a segments. Finally, the spectra were resampled onto a single wavelength scale with 0.04Å binning and coadded, weighting each by the inverse of the statistical variance of the data determined over intervals of 20Å.

2.2 Absorption features in the co-added FUV spectrum of GD71

The co-added FUSE spectrum has been run through a series of custom written scripts to (1) normalize the data, (2) flag probable absorption features, (3) fit Gaussians or where appropriate multiple Gaussians to determine central wavelengths and equivalent widths of features and (4) assign each feature a likely identification based on the measured radial velocity and the ionization state

Table 2. Summary details of the main absorption features identified in the coadded FUSE spectrum of the white dwarf GD71

Ion	Lab	Obs	v	Δv	E.W.	ΔE.W.
	Å		kms^{-1}		mÅ	
Interstellar						
HI	917.181	917.196	4.9	4.9	168	19
HI	918.129	918.130	0.3	4.1	135	16
HI	919.351	919.356	1.6	4.9	156	11
HI	920.963	920.959	-1.3	4.6	180	11
HI	923.150	923.152	0.6	8.3	194	12
HI	926.226	926.234	2.6	2.3	175	14
HI	930.748	930.728	-6.4	1.3	161	14
HI	937.803	937.780	-7.4	1.0	151	13
HI	949.743	949.747	1.3	1.3	175	13
OI	976.448	976.421	-8.3	1.5	10	4
CIII	977.020	977.013	-2.1	1.5	41	6
NIII†	989.799	989.838	11.8	3.9	31	4
SiII†	989.873	989.838	-10.6	3.9	31	4
CII	1036.337	1036.334	-0.9	0.6	56	2
OI	1039.230	1039.242	3.5	1.5	11	2
NII	1083.990	1084.016	7.2	1.0	28	4
NI††	1134.165	1134.155	-2.6	5.7	4	2
NI††	1134.415	1134.426	2.9	1.8	17	3
NI††	1134.980	1134.997	4.5	1.2	15	2
FeII	1144.938	1144.948	2.6	3.7	4	2
Photospheric						
PIII	1003.600	1003.615	4.5	5.1	5	2
PV	1117.977	1117.985	2.1	2.8	13	3
PV	1128.008	1128.020	3.2	1.7	4	2

† Blended ?
†† Some contamination from NI geocoronal emission

of the proposed progenitor species. The results of this process are summarised in Table 2. We note that the 1-σ errors in central wavelengths, derived from a χ^2 fitting process, underestimate the true uncertainties as illustrated by the scatter in the velocity measurements. We believe this discrepancy is due mainly to residual uncertainties in the FUSE pipeline wavelength calibration and small imperfections in our alignment of the spectral segments.

Holberg et al. (1998) reported the detection of interstellar OI (1302.169Å) and SiII (1190.416,1260.442Å) in the IUE echelle spectrum of GD71 and determined a weighted mean velocity of +23.2±2.5kms^{-1} for these features. Based on observations of objects with independently determined radial velocities, the absolute wavelength scale of IUE echelle data processed with NEWSIPS is found to be accurate to 3-5kms^{-1} (Holberg et al. 1998). The nominal absolute calibration of the FUSE wavelength scale is considered to be limited to ∼15kms^{-1} by uncertainty in the position of the target within the LWRS aperture (e.g Oegerle et al. 2005). We have determined a weighted mean velocity of -0.3±0.6kms^{-1} for the low ionization lines of CII (1036.337Å) and OI (1039.230Å) which lie within the wavelength range covered by the LiF 1a segment (987.1-1082.3Å) and almost certainly have the same origin as the lines reported by Holberg et al. Since these results indicate an offset in the FUSE data of ≈-20kms^{-1} with respect to the more robust wavelength scale of the IUE echelle spectrum in subsequent discussion we apply a systematic shift of +23.5±2.6kms^{-1} to the velocities determined from the former.

Unfortunately, high resolution spectroscopic measurements of the core of the H-α line formed in atmosphere of GD71 indicate that the stellar photosphere has a similar velocity (e.g. the

Table 3. Results of homogeneous model fitting proceedure.

Star	$T_{\rm eff}$	log g	[P/H]
GD71	32625^{+15}_{-25}	$7.89^{+0.01}_{-0.01}$	$-8.57^{+0.09}_{-0.13}$
RE J1918+595	32030^{+95}_{-95}	$7.79^{+0.03}_{-0.04}$	$-8.70^{+0.23}_{-0.37}$
RE J0605-482	34370^{+190}_{-175}	$7.79^{+0.06}_{-0.05}$	$-8.36^{+0.14}_{-0.19}$

weighted mean of the measurements of Maxted et al. 2000 is +30.0±1.5kms^{-1}) to the interstellar medium (ISM) along this line of sight (+23.2±5.6kms^{-1} allowing for a potential uncertainty of 5kms^{-1} in the absolute calibration of the IUE echelle data). Thus radial velocities alone are not a suitable method for distinguishing between a photospheric and an interstellar origin for absorption features detected in this particular FUSE dataset. Nevertheless, when the comparatively high effective temperature of GD71, the low ionization states of the progenitor species and previously published results based on FUSE observations of DA white dwarfs (e.g. Lehner et al. 2003) are taken into account the vast majority of lines listed in Table 2 can be attributed to the ISM.

2.3 High ionization phosphorus lines in the FUSE spectrum of GD71

A closer inspection of the coadded FUSE spectrum has also revealed several weak features arising from species of relatively high ionization states e.g. the resonance lines of PV at 1117.977Å and 1128.008Å. The velocities of these transitions are identical within the measurement uncertainties so they probably have a common origin (see Table 2). Although these lines are coincident in velocity space with a number of features attributable to the ISM, residual uncertainties in the wavelength calibration of this dataset and the similarity between the velocities of the ISM along this line of sight and the atmosphere of GD71, as discussed above, mean that an interstellar, circumstellar or photospheric origin cannot be ruled out at this stage. Nevertheless, other considerations indicate the former interpretation is unlikely. For example, the ionization stages of the progenitor ions are higher than those typically found in the ISM. The PIII 1003.600Å line arises from the $2P^o$-2S multiplet and has a lower level 0.07eV above the ground state. Furthermore, in a solar mixture P is less abundant by a factor 1000 than C, N or O.

To examine the two other possible origins in more detail, we have acquired from MAST the FUSE data products for two further white dwarfs with similar effective temperatures and surface gravities to GD71. Vennes et al. (1997) derive $T_{\rm eff}$=33000K, log g=7.90 for REJ1918+595, while Marsh et al. (1997), Finley et al. (1997) and Vennes et al. (1997) derive $T_{\rm eff}$=33040K, log g=7.80, $T_{\rm eff}$=35332K, log g=7.84 and $T_{\rm eff}$=35600K, log g=7.76 respectively for RE J0605-482. FUV observations of RE J1918+595 and RE J0605-482, in TTAG mode and in the LWRS configuration were obtained on 2002/05/07 and 2002/12/31 respectively.

For each of these two stars we have constructed a co-aligned and co-added the FUSE spectrum in the manner described above. In each dataset we have determined the velocities of features attributable to the ISM, e.g. NI (1134.165, 1134.415, 1134.980Å), FeII (1144.938Å) and the stellar photosphere e.g. SiIII (1108.368, 1109.957, 1113.219Å) and SiIV (1122.485, 1128.340Å), where the rest wavelengths of the Si lines are determined from the predictions of appropriate non-LTE model atmospheres. The weighted mean velocities of these interstellar and photospheric lines in the spectrum of RE J1918+595 are +23.5±0.3kms^{-1} and

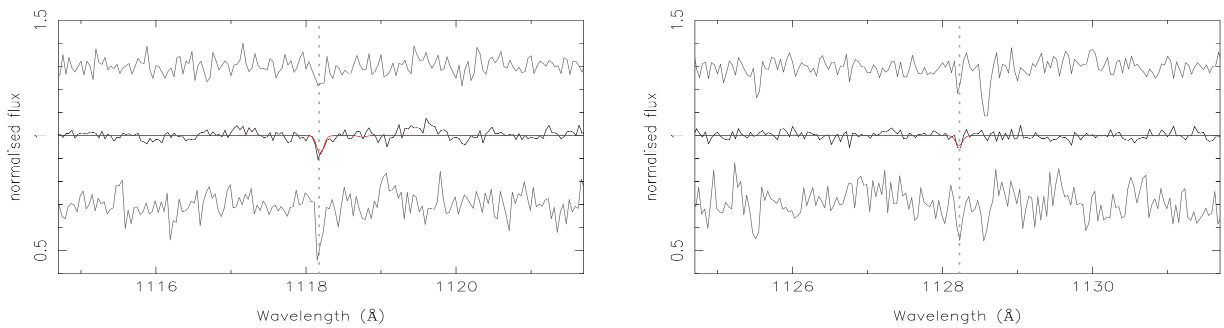

Figure 1. Sections of the normalised FUSE spectra of REJ1917+599 (top), GD71 (middle) and REJ0605-482 (bottom) showing the resonance lines of PV (1117.977,1128.008Å) which we attribute to the stellar photospheres. Photospheric SiIV (1128.334Å) and interstellar FeII (1125.448Å) lines are also seen in the top and bottom datasets. The best fit model representation of the GD71 data is overplotted (red).

+59.8±0.9kms^{-1} respectively. In the spectrum of RE J0605-482 these features have weighted mean velocities of +18.2±0.7kms^{-1} and +53.1± 2.8kms^{-1} respectively. Thus in the spectra of these two objects, the ISM and the photosphere have quite distinct velocities.

Scrutiny of the data for RE J1918+595 and RE J0605-482 reveals the presence of PV resonance lines, at weighted mean velocities of +55.3±1.5kms^{-1} and +53.7±0.6kms^{-1} respectively. A previous high resolution UV study has revealed circumstellar features along the lines of sight to nine out of a sample of 23 hot DA white dwarfs (Bannister et al. 2003). In the vast majority of these 9 cases the difference in the velocities of the circumstellar and interstellar features was found to be less than 10kms^{-1}. The difference in velocity between the PV transitions and the ISM lines in the FUSE spectra of RE J1918+595 and RE J0605-482 are 31.8±1.5kms^{-1} and 35.5±3.0 kms^{-1} respectively, arguing against a circumstellar origin. Indeed, given the scatter typically seen in our measurements, the velocities of the PV lines strongly support a photospheric interpretation. In Figure 1 we show sections of the FUSE spectra of GD71, RE J1918+595 and RE J0605-482 centered on the PV resonance transitions. For the purposes of this plot we have applied a shift to the wavelength scales to co-align the 1117.977Å line in the three datasets.

On the weight of the above evidence, we conclude that the most likely origin of the high ionization P lines identified in the FUSE spectrum of GD71 is the stellar photosphere. Accepting this, we now use model atmosphere calculations to place constraints on the abundance of photospheric phosphorus in these three DAs.

3 THE MODEL ATMOSPHERE CALCULATIONS

The models utilised in this work have been generated with the latest versions of the plane-parallel, hydrostatic, non-LTE atmosphere and spectral synthesis codes TLUSTY (v200; Hubeny 1988, Hubeny & Lanz 1995, Hubeny & Lanz private comm.) and SYNSPEC (v48; Hubeny et al. 1994). We have employed state-of-the-art model ions of H and P. The HI ion incorporates the 8 lowest energy levels and one superlevel extending from n=9 to n=80, where the dissolution of the high lying levels was treated by means of the occupation probability formalism of Hummer & Mihalas (1988), generalised to the non-LTE situation by Hubeny, Hummer & Lanz (1994). The PIV and PV model ions were developed by Lanz & Hubeny (2003) for the study of O-stars and full details may be found therein. The PIII ion, which incorporates the 9 lowest levels, was constructed in a similar manner, except the online version of AUTOSTRUCTURE[1] was used to estimate oscillator strengths where experimental values were unavailable. All calculations were carried out under the assumption of radiative equilibrium and incorporated a full treatment of line blanketing effects. During the calculation of the model structure the lines of the Lyman and Balmer series were treated by means of an approximate Stark profile but in the spectral synthesis step, detailed profiles for the Lyman lines were calculated from the Stark broadening tables of Lemke (1997).

Numerous estimates of the effective temperature and surface gravity of GD71 are available in the literature e.g. Marsh et al. (1997), Finley et al. (1997) and Vennes et al. (1997) derive $T_{\rm eff}$=32008K, log g=7.70, $T_{\rm eff}$=32747K, log g=7.68 and $T_{\rm eff}$=33000K, log g=7.88 respectively by fitting synthetic profiles to the observed Balmer lines. Hence we generated a grid of H+P models spanning the ranges $T_{\rm eff}$=30000-35000(2500)K, log g=7.5-8.5(0.5) and [P/H]=-12 – -7.0(1.0). Our general spectral analysis techniques have been described at length in previous publications. so only aspects specific to the current work are detailed here. For computational speed, only the regions of the co-added, optimal S/N, dataset which include the Lyman lines and the locations of the phosphorus transitions predicted to be most prominent in this effective temperature and surface gravity range were incorporated into the spectral fitting process (e.g. 930-990Å, 1000-1050Å 1116-1120Å and 1126-1130Å). During the analysis, each of these sections was assigned an independent normalisation parameter to circumvent any residual errors in the shape of the continuum flux. All errors quoted here are 1σ unless stated otherwise but as these are derived formally from the fitting process, they may underestimate the true uncertainties. The parameters of our best fitting homogeneous model representations of the FUSE spectra of all three white dwarfs are given in Table 3. We note that the energy distribution of the GD71 model is indistinguishable from that of a pure-H composition from 10-10000Å, except in a few narrow regions which include P lines.

4 DISCUSSION

4.1 Photospheric phosphorus in DA white dwarfs

Bruhweiler (1984) reported the possible detection of NV, CIV and SiIV resonance lines in a single IUE spectrum of GD71 but concluded that these were most likely formed in a halo region around the star. A subsequent examination of a coadded dataset derived

[1] http://random.ivic.ve/autos/

from the three existing IUE echelle spectra failed to confirm the existence of these features at the 30 mÅ equivalent width level and instead detected only the strong resonance lines of interstellar OI and Si II (Holberg et al. 1998). Hence the current work represents the first probable detection of a heavy element in the atmosphere of the flux standard star GD71.

Phosphorus was first revealed in the atmospheres of the hot DA white dwarfs G191-B2B and MCT0455-2812 by far ultraviolet ORFEUS observations (Vennes et al. 1996). Subsequently, photospheric phosphorus has been reported in the FUSE spectra of a significant number of other hot ($T_{\rm eff}\gtrsim$40000K) hydrogen rich degenerates (e.g. GD246, Feige 55, Wolff et al. 2001 and RE1032+532, Dupuis et al. 2004). However, to date, phosphorus has been detected in the atmospheres of only two DAs with $T_{\rm eff}$ $<$40000K, GD394 ($T_{\rm eff}\approx$39500K; Chayer et al. 2000) and GD659 ($T_{\rm eff}\approx$36000K; Dupuis et al. 2004). The white dwarfs analysed in this paper, therefore, represent the three coolest DAs in which photospheric phosphorus has yet been found.

4.2 Possible mechanisms for photospheric phosphorus in these white dwarfs

While the presence of a close cool companion can lead, through accretion of wind material, to heavy element contaminatation in a white dwarf atmosphere (e.g. V471 Tauri; Sion et al. 1997) it seems rather unlikely that this is the source of the phosphorus observed in these stars. For example, Maxted et al. (2000) find no evidence of radial velocity variations in GD71, while Dobbie et al. (2005) have used near-IR spectroscopy to set a limit of $M<0.072M_{\odot}$ on the mass of any such companion. Furthermore, 2MASS data provides no evidence of a near-IR excess to either REJ1917+488 or REJ0605-482 (e.g. Skrutskie et al. 1997). While the presence of a close substellar companion to any of these stars cannot be excluded, recent work by Farihi et al. (2005) argues against this.

Alternatively, equilibrium radiative levitation calculations indicate that observable quantities of phosphorus should be supported in the photospheres of typical DA white dwarfs to $T_{\rm eff}\approx$32500K (Vennes et al. 1996). Indeed, the phosphorus abundances we measure for these three stars seem to be satisfyingly consistent with the theoretical values (see their Figure 4). At face value, the lowest and largest abundance is measured in the coolest and hottest star respectively. However, the results of a preliminary study of the FUSE spectra of 28 hot DA white dwarfs indicate that this agreement might be simply fortuitous. In many objects with 35000K$\lesssim T_{\rm eff}\lesssim$55000K, phosphorus is found to be underabundant, often strongly, with respect to the predictions (Dupuis et al. 2004). The abundance of an element, in equilibrium, is generally depth dependent (e.g. Schuh 2005). The predictions of Vennes et al. (1996) correspond to the phosphorus abundance at the Rosseland photosphere ($\tau_{\rm Ross}\approx$2/3), which may differ significantly from that in the line formation region from which the observed abundances are determined. Therefore, to appraise the rôle of radiative levitation in more detail we have constructed a small number of fully self-consistent H+P model atmospheres. In these calculations we have used information on the ionization fraction of phosphorus and the detailed radiation field gleaned from SYNSPEC to determine the effective gravitational downward forces and the upward radiative forces on phosphorus ions as a function of depth in the atmosphere. An estimate of the phosphorus abundance at each depth point has been obtained by equating these forces (e.g. Chayer et al. 1995b). The estimates have been fed back into TLUSTY and an updated model structure determined. The entire process has been repeated until the abundances converge to $\lesssim$3% throughout most of the atmosphere. In the uppermost layers this restiction has been relaxed to $\lesssim$10% but has no significant impact on the emergent spectrum.

The results of these calculations consolidate previous predictions that detectable levels of phosphorus remain supported in the atmospheres of typical DA white dwarfs at the effective temperatures examined here. However, the metal absorption lines predicted by our non-LTE models are considerably stronger than those observed in the FUSE data. For example, if we attempt to fit our homogeneous grid to the emergent spectra from the self-consistent calculations with effective temperatures and surface gravities appropriate to RE J1918+595 and GD71, we derive [P/H]$\approx$-7.3. If instead we fit the self-consistent models to the observed phosphorus features only, fixing the effective temperature at the values determined in §3.1, we find the element abundance profile appropriate to log g=8.43, 8.44 and 8.45 provides the best representation of these data, for RE J0605-482, GD71 and RE J1918+595 respectively. These gravities are greater by $\sim$0.6 dex than those estimated from the Lyman line series. The apparent discrepancy between the results from our modelling and the predictions of Vennes et al. (1996) likely stems from the abundance of phosphorus at the Rosseland photosphere, $\log_{10}$ (model column mass depth) $\sim$ -2, decreasing rapidly with effective temperature at $T_{\rm eff}\lesssim$35000K, while in the P line forming region, $\log_{10}$ (model column mass depth) $\sim$ -3.5, maintaining a greater value.

Interestingly, in their analysis of the EUVE spectra of 26 DA white dwarfs ($T_{\rm eff}$ $\gtrsim$40000K), where a grid of self-consistent stratified models was compared by eye to the data, allowing effective temperature and surface gravity to, in effect, vary freely, Schuh et al. (2002) found, more often than not, the calculation which best represented the observed energy distribution of a white dwarf had a larger surface gravity ($\sim$0.4 dex) than the value determined for the star via Balmer line fitting. Schuh (2005) has estimated that the complexities in accurately calculating the radiative force on an element in a stellar photosphere, e.g. due to the opacities of other metals, can result in uncertainties of up to 2 dex in the abundances derived at some depth points in their calculations. We note that the three white dwarfs analysed here are more metal poor and somewhat cooler than those typical of her sample, lying in a range where non-LTE models replicate the structure of the stellar photosphere more satisfactorily (Barstow et al. 2003b). Indeed, test calculations reveal that the inclusion of additional metals, e.g. C and Si, has no significant impact on the P abundance profile. However, robust and comprehensive atomic data for P are not available from TOPBASE (Cunto & Mendoza 1992) so shortcomings in the current model ions and linelists for this element may counter any advantage here.

Of course the balance between radiative levitation and gravitational settling can be disturbed by massloss. From a series of exploratory time dependent calculations involving Si, Chayer et al. (1997) find that at moderate mass loss rates ($10^{-16}\lesssim\dot{\rm M}\lesssim10^{-14}{\rm M}_{\odot}$ yr^{-1}), the reservoir of this element is exhausted after a few$\times10^{4}$ years, after which it is depleted rapidly from the stellar photosphere (few$\times10^{5}$ yrs) to levels well below the detection threshold of the FUSE data. At very low rates of massloss (e.g. $\dot{\rm M}\lesssim10^{-18}{\rm M}_{\odot}$ yr^{-1}) the Si abundance profile is essentially that predicted by equilibrium radiative levitation theory up to the end of their calculations. The mere detection of phosphorus in these three stars would appear to argue against massloss at the larger rates discussed above. Nevertheless, it seems plausible that this process may be operating at low levels in these stars and that it is the slow exhaustion of an underlying reservoir of this element which results in observed abundances below the equilibrium radiative levitation prediction.

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REFERENCES

Barstow, M.A., Dobbie, P.D., Holberg, J.B., Hubeny, I. & Lanz, T., 1997, MNRAS, 286, 58
Barstow, M.A., Good, S.A., Holberg, J.B., Hubeny, I., Bannister, N.P., Bruhweiler, F.C., Burleigh, M.R. & Napiwotzki, R., 2003a, MNRAS, 341, 870
Barstow, M.A., Good, S.A., Burleigh, M.R., Hubeny, I., Holberg, J.B. & Levan, A.J., 2003b, MNRAS, 344, 562
Bannister, N.C.,Barstow, M.A.,Holberg, J.B. & Bruhweiler, F.C., 2003, MNRAS, 341, 477
Bohlin, R.C., 1996, AJ, 111, 1743
Bohlin, R.C., Dickensen, M.E. & Calzetti, D., 2001, AJ, 122, 2118
Bruhweiler, F.C. & Kondo, Y., 1983, ApJ, 269, 657
Chayer, P., Vennes, S., Pradhan, A.K., et al., 1995b, ApJ, 454, 429
Chayer, P., Fontaine, G. & Wesemael, F., 1995b, ApJS, 99, 189
Chayer, P., Fontaine, G. & Pelletier, C., 1997, in White Dwarfs, Proc. of 10th European Workshop on White Dwarfs, eds. Isern, Hernanz, Garcia-Berro, 214, p253, Kluwer
Chayer, P., Kruk, J.W., Ake, T.B., Dupree, A.K., Malina, R.F., Siegmund, O.H.W., Sonneborn, G. & Ohl, R.G., 2000, ApJL, 538, 91
Cunto, W. & Mendoza, C., 1992, Rev. Mexicana Astron. Af., 23, 107
Dobbie, P.D., Burleigh, M.R., Levan, A.J., Barstow, M.A., Napiwotzki, R., Holberg, J.B., Hubeny, I., Howell, S.B., 2005, MNRAS, 357, 1049
Dupuis, J., Fontaine, G., Pelletier, C., Wesemael, F, 1993, ApJS, 84, 73
Dupuis, J., Chayer, P., Kruk, J.W. & Vennes, S., 2004, in White Dwarfs, Proc. of NATO ARW on White Dwarfs, eds. de Martino, Silvotti, Solheim, Kalytis, v105, p157, Kluwer
Farihi, J., Becklin, E.E. & Zuckerman, B., 2005, ApJS, accepted (astro-ph/0506017)
Finley, D.S., Koester, D. & Basri, G., 1997, ApJ, 488, 375
Giclas, H.L., Burnham, R. & Thomas, N.G., 1965, Lowell Observatory Bulletin, 125, p155-164
Green, J.C., Wilkinson, E. & Friedman, S.D. 1994, Proc. SPIE, 2283, 12
Holberg, J.B., Hubeny, I., Barstow, M.A., Lanz, T., Sion, E.M. & Tweedy, R.W., 1994, ApJL, 425
Holberg, J.B., Barstow, M.A. Bruhweiler, F.C. & Collins, J., 1996, AJ, 111, 2361
Holberg, J.B., Barstow, M.A., Lanz, T. & Hubeny, I., 1997, ApJ, 484, 871
Holberg, J.B., Barstow, M.A. & Sion, E.M., 1998, ApJS, 119, 207
Hubeny, I., 1988, Comput. Phys. Commun. 52, 103
Hubeny, I., Hummer, D. & Lanz, T., 1994, A&A, 282, 151
Hubeny, I., Lanz, T & Jeffrey, C.S., 1994, in Jeffrey, C.S., ed, Newsletter on Analysis of Astornomical Spectra No. 20, St. Andrews Univ., p. 30
Hubeny, I. & Lanz, T., 1995, ApJ, 439, 875
Hummer, D. & Mihalas, D., 1988, ApJ, 331, 794
Landolt, A.U., 1992, AJ, 104, 340
Lanz, T. & Hubeny, I., 2003, ApJS, 146, 417
Lehner, N., Jenkins, E.B., Gry, C., Moos, H.W., Chayer, P. & Lacour, S., 2003, ApJ, 595, 858
Lemke, M., 1997, A&AS, 122, 285
Marsh, M.C., Barstow, M.A, Buckley, D. A., Burleigh, M. R., Holberg, J. B., Koester, D., O'Do noghue, D., Penny, A. J. & Sansom, A. E., 1997, MNRAS, 287, 705
Maxted, P.F.L., Marsh, T.R. & Moran, C.K.J., 2000, MNRAS, 319, 305
Oegerle, W.R., Jenkins, E.B., Shelton, R.L., Bowen, D.V. & Chayer, P., 2005, ApJ, 622, 377
Schatzman, E., 1958, in White Dwarfs, North Holland Publishing Co., Amsterdam
Schuh, S., Dreizler, S. & Wolff, B., 2002, A&A, 382, 164
Schuh, S., 2005, Thesis dissertation, University of Tübingen
Sion, E M., Schaefer, K G., Bond, H E., Saffer, R.A. & Cheng, F.H. 1998, ApJL, 496, 29
Skrutskie, M. F., et al. 1997, in The Impact of Large Scale Near-IR Sk y Surveys, ed. F. Garzon et al. (Dordrecht: Kluwer), 25
Vauclair, G., Vauclair, S. & Greenstein, J.L., 1979, A&A, 80, 79
Vennes, S., Chayer, P., Thorstensen, J.R., Bowyer, S. & Shipman, H.L., 1992, ApJ, 392, 27
Vennes, S., Chayer, P., Hurwitz, M. & Bowyer, S., 1996, ApJ, 468, 898
Vennes, S, Thejll, P.A., Galvan, R.G. & Dupuis, J, 1997, ApJ, 480, 714
Wolff, B., Kruk, J.W., Koester, D., Allard, N.F., Ferlet, R. & Vidal-Madjar, A., 2001, A&A, 373, 674
Zuckerman, B., Koester, D., Reid, I.N. & Hunsch, M., 2003, AJ, 506, 477

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